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Strategy on choice of layback spins in figure skating

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Abstract
Spin is an important component of figure skating, one of the most elegant events in the Winter Olympic Games. It is always presented as an example of the conservation of angular momentum in mechanics textbooks. However, the physics behind it in the actual operation is not that simple. Herein, we analyzed videos of an elite figure skater with open source video analysis. The moments of inertia of her body in six different layback positions were obtained. The average ice resistance during her spin was found to be about 26*N* and was put into consideration in the following calculation. Twenty-two different layback spins that score the same basic value were discussed. The initial angular momentum a skater needs when executing a spin is considered to be the largest contributor to its difficulty; the suggested easiest spin among the 22 was thus found by comparing their initial angular momentum. This paper presents a strategy that may help figure skaters achieve a high-scored layback spin efficiently, and the process itself will be an inspiring example of applying theory to practice for physics students.

Keywords: moment of inertia, angular momentum, figure skating, layback spin, ice resistance

S Supplementary material for this article is available online

(Some figures may appear in colour only in the online journal)

1. Introduction

Examples beyond the textbook always inspire students to explore the physics behind them. Rain [1], bicycle tyres [2], ping-pong balls [3] and even the fluid in a drinking straw [4] can be

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interesting examples for this. The physics behind sports such as springboard diving [5], sailing [6] or ice hockey [7] is an attractive area, as well. Such challenging yet solvable problems will give students a sense of achievement, especially when the result they get is helpful in real life. Here we focus on an elegant and popular sport—figure skating.

As an ice sport, figure skating is an official event in the Winter Olympic Games, and spin is an important component of its technical elements. Among the kinds of spin, the layback spin is a signature spin of female skaters, where the athlete leans her upper body back or sideways and performs a series of variants such as grabbing the skate blade or even lifting it over head, as shown in the supplementary videos (https://stacks.iop.org/EJP/42/025806/mmedia). In classical mechanics textbooks, spin in figure skating is always presented as an example of the conservation of angular momentum [8]. When a skater moves her leg and arms close to the spinning axis, the moment of inertia of this position is much smaller than the stretched one. Since the friction of ice is considered to be negligible, a decrease of the moment of inertia will lead to an increase of angular velocity: then a speed-up can be clearly observed. This is the common explanation in textbooks, while spin in practice is not that simple.

So far, a considerable literature has grown around figure skating. Efforts have been made to investigate the sport's injuries [9–13], to explain the physics behind it [14–19], to invent new related apparatuses [20, 21], to simulate the skating motions [22], and to explore the skills involved in the actual operation of technical elements like jumps and spins [23–27]. However, little quantitative analysis of the moment of inertia, a dominant feature of spins, of the human body in any spinning positions, has been undertaken; previous works on which have been mostly restricted to qualitative comparisons. Furthermore, contrary to the simplified models in textbooks, ice resistance in spins is much larger than that in glides owing to the extra contact between the ice and the toe pick, so the external torque cannot be neglected. Spin in practice is a process with constant consumption of angular momentum, while very little attention has been paid to the consumption and its relationship with the degree of difficulty of a spin. According to the International Skating Union (ISU) regulations, a large number of different layback spins in the same level can get the same basic value, so strategy on choosing an easier layback spin among the same-scored ones becomes a crucial issue for consideration.

This paper attempts to give a method to get the moment of inertia of the human body in any given spinning position, and to find a way to assess the degree of difficulty of various layback spins in order to find the most efficient spin among the same-scored ones. It is hoped that this study will help skaters find the most efficient approach to high-scored layback spins, and help students enhance their abilities at solving real-life problems with what they have learned in the classroom.

2. Methods

Data for this study were collected with open source video analysis (physlets.org/tracker/). The layback spin videos of an elite Chinese skater were downloaded from the Internet with a resolution no less than 1280 × 720 and a sampling rate of 24 frames per second. The skate boot was used as a calibration stick to set the scale. After setting the appropriate coordinate system, when manually marking a point in any of the frames, the software will give the coordinate and time, which will be recorded and used for the following calculations.

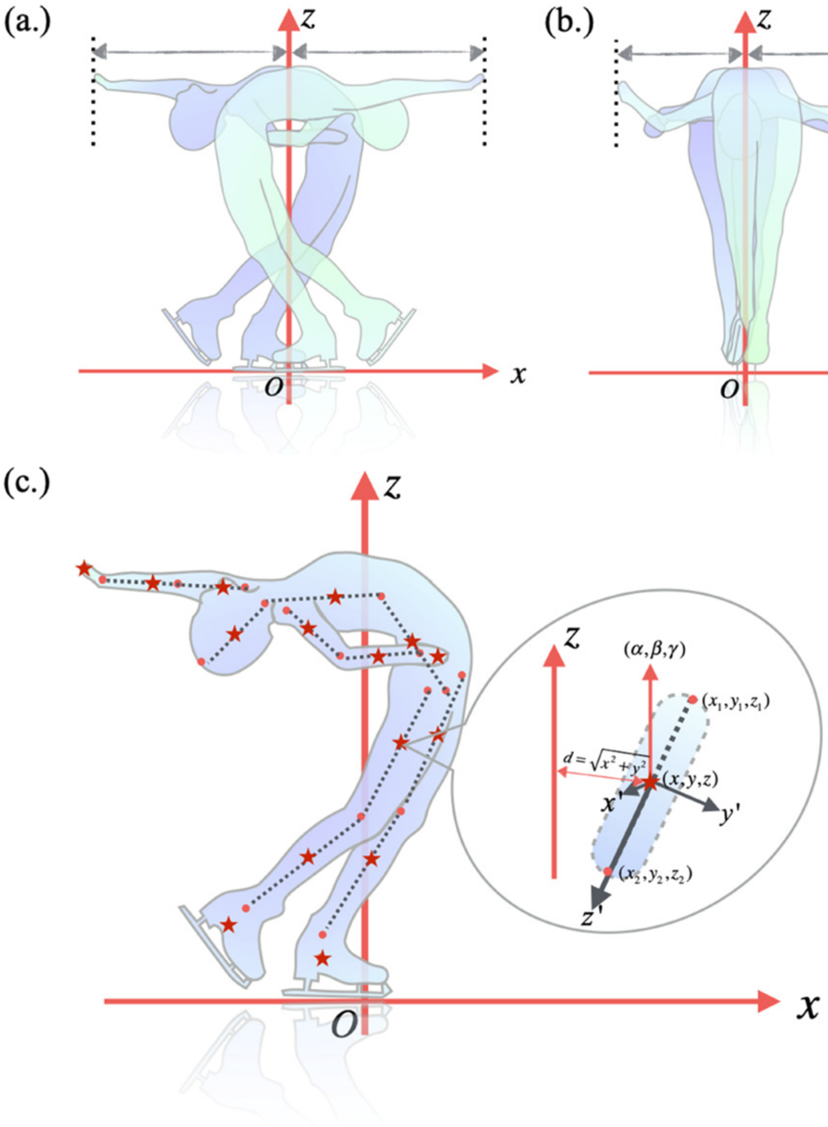

Figure 1. (a) Spinning axis in the x-z coordinates. (b) Spinning axis in the y-z coordinates. (c) Start and end points are marked with dots; stars represent the centers of mass; the enlarged region is the thigh segment as an example, indicating the definition of distance and orientation angle of the segments.

3. Moment of inertia

The human body can be divided into a group of body segments. Divisions of the human body are different in the number of segments and the selection of start and end points of each body segment among different standards. Here we applied the standard from the Chinese National Standard about inertial parameters of adult human body (CNS) since the layback spin we investigate is executed by a Chinese skater. The CNS divides the human body into 15 segments

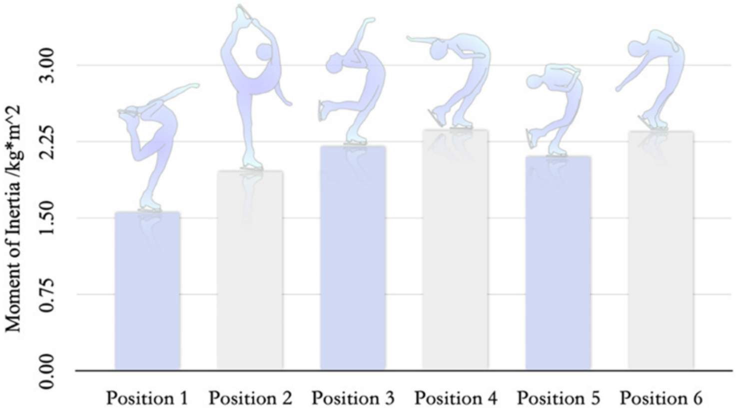

Figure 2. Moment of inertia of six positions.

and gives the relative mass, relative location of center of mass and the regression equation of the moments of inertia about the coronal axis, sagittal axis and vertical axis of each body segment [28].

We focused on six layback positions that the skater frequently performed, as indicated in figure 2. The frames where the skate blade of the skater is parallel and vertical to the screen were selected, and coordinate systems were created as indicated in figures 1(a) and (b). According to the division standard of CNS, we marked the start and end points of all her body segments in the selected frames with Tracker software, as illustrated in figure 1(c). After marking the start points (x_1, y_1, z_1) and end points (x_2, y_2, z_2) of all the body segments, as shown in figure 1(c), the coordinates of their mass center (x, y, z) were obtained from the relative location of the center of mass [28]. With the height and weight of the skater, the moments of inertia about the coronal axis, sagittal axis and vertical axis I_x, I_y, I_z of all the segments were determined [28]. These are considered to be the principle moments of inertia of body segments owing to the symmetry of the human body. The mass of each segment was obtained by multiplying the relative mass and the weight of the skater [28].

The value of the moment of inertia depends on the spinning axis [29]. Given the direction cosines of a certain axis α, β, γ, the moment of inertia about this axis can be described as

$$I_\mathrm{c} = (\alpha, \beta, \gamma) \begin{pmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \\ \gamma \end{pmatrix} = I_x\alpha^2 + I_y\beta^2 + I_z\gamma^2, \tag{1}$$

where γ is determined by the equation

$$\gamma = \frac{z_1 - z_2}{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}}. \tag{2}$$

It is difficult to measure α and β directly, but fortunately the values of I_x and I_y for most body segments are almost the same [28], so errors of estimation of α and β are acceptable. Then, the moment of inertia about the spinning axis is given by

$$I_i = I_\mathrm{c} + md^2, \tag{3}$$

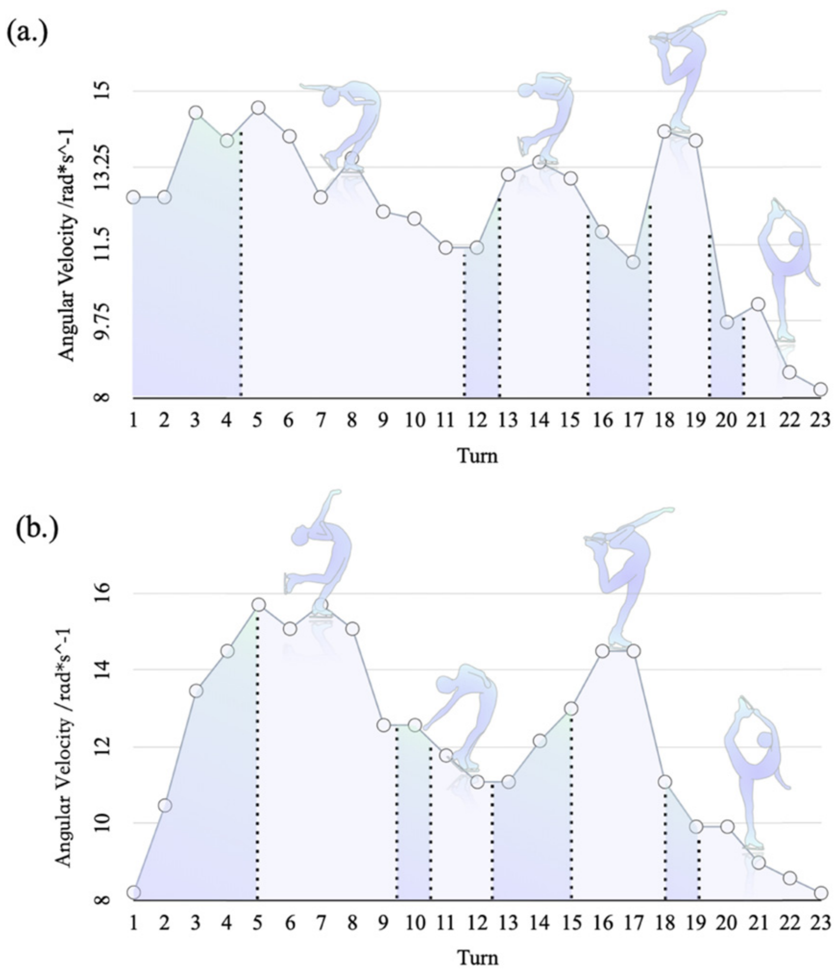

Figure 3. (a) Change of average angular velocity of each turn during a layback spin. Light blue region suggests that the skater keeps spinning in a certain position, and the dark blue region is the transition from one position to another. Symbols above the curve indicates in which position the skater is spinning. (b) Change of average angular velocity of each turn during another layback spin.

where ***m*** is the mass of the body segment, and ***d*** refers to the distance between the mass center of the body segment and the spinning axis. Finally, for the moment of inertia of the human body, we have

$$I = \sum_{i=1}^{n} I_i. \tag{4}$$

Results are shown in figure 2. Position 1 and Position 2 have a smaller moment of inertia than the others. This result can partially explain why skaters usually execute these two positions at the end of a spin. At the end of the spin, the angular momentum is not as large as that at the beginning, so skaters execute the positions with less moment of inertia in order to maintain enough angular velocity to keep balance.

Furthermore, we analyzed the change of average angular velocity of each turn during two related layback spins executed by the skater; the videos can be found in the supplementary information [30, 31]. As shown in figures 3(a) and (b), both spins are composed of four different layback positions whose moment of inertia have been obtained in figure 2. In figure 3(a), for example, four turns after she started her spin, she made herself in Position 4. She then kept this position for eight turns, and changed positions from 4 to 5. The transition took about one turn, then she kept spinning in Position 5 for more than three turns, and changed to Position 1.During the transition, the upward/downward tendency of angular velocity accords with the moments of inertia we calculated of the six positions. Take the transition from Position 4 to Position 5 as an example, from Turn 11 to Turn 13, illustrated in figure 3(a), the upward tendency of angular velocity indicates that the moment of inertia of Position 5 is lower than that of Position 4, which is consistent with the result we got. Further, we noticed the impact of ice resistance which leads to a slowdown when the skater remains spinning in a certain layback position, as shown in Turn 4 to Turn 12 in figure 3(a). Interestingly, sometimes there is a speed-up at the beginning of a new position. When the skater starts to spin in a new position, she cannot adjust to the right position at once: her free leg is further from the axis than usual. The adjustment to move her free leg to the right position closer to the axis takes about one turn and a speed-up is thus discovered.

4. Ice resistance

In another sport mentioned in the previous section, springboard diving is a good example of the conservation of angular momentum owing to the negligible air resistance. The angular velocity of athletes will be higher when they contract and lower when they stretch. More importantly, if they maintain a constant posture, the angular velocity will also remain constant until they jump into the water; but this is not the case during a spin in figure skating. When a skater maintains a posture from the beginning to the end, the angular velocity will gradually decrease until it is too low to keep balance, which can be seen in the last video in the supplementary information [32]. Therefore, figure skaters in practice usually start with a stretching position and end with a contracting one in order to maintain a high angular velocity.

The friction between ice and skate blade in gliding is usually considered to be negligible, but things do not work this way in spins. As shown in figure 4(a), when executing a spin, ice contacts with the blade (point B) and toe pick (point A) at the same time. The coefficient of friction between the ice and blade is small enough to be negligible [19], which is the case in gliding, while the friction between the ice and toe pick is much larger. In addition, spins in figure skating are nothing like a screw: they do not spin at a fixed point but, instead, idraw a spiral around an axis continuously, as indicated in figure 4(b), which can also be observed in the videos in the supplementary information [26, 30–32]. These two factors make the torque not negligible.

For a spin with torque, we have

$$\int_{t_1}^{t_2} M \, \mathrm{d}t = L_2 - L_1, \tag{5}$$

where the net external torque

$$M = \sum_{i=1}^{n} (r_i \times F_i) \tag{6}$$

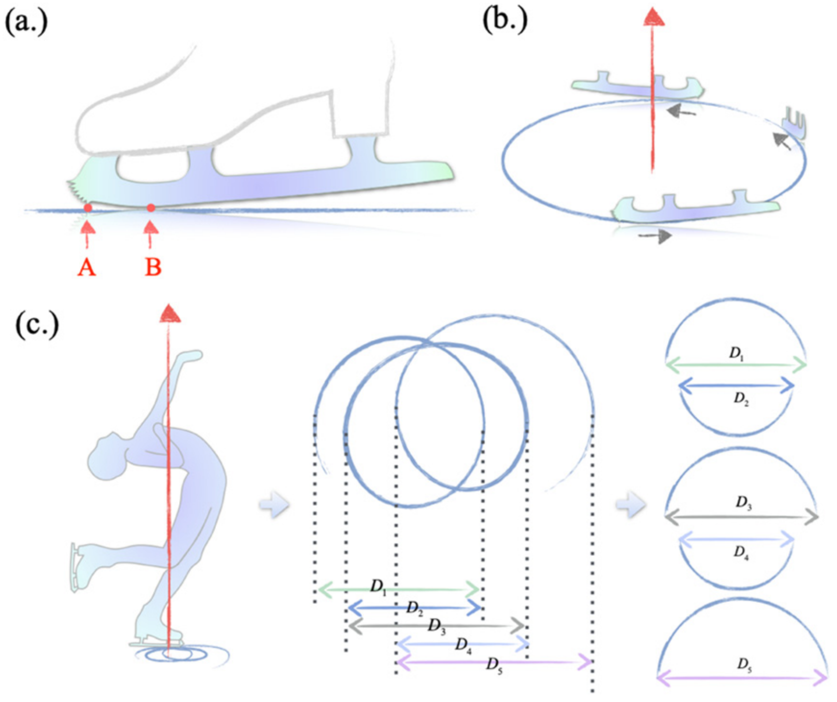

Figure 4. (a) Magnification of the skate boot in a spin, blade (point B) and toe pick (point A) contact with ice at the same time. (b) The skate blade drawing a spiral on the ice around the spinning axis rather than spinning at a fixed point. (c) Measurement and approximation of rotation diameters (distance between the toe pick and the spinning axis).

and L_1, L_2 represent the initial and terminal angular momentum, respectively. Angular momentum is written as

$$L = I\omega. \tag{7}$$

Due to the fairly low air resistance, ice resistance can be seen as the external force in a spinning process. Suppose the friction f in a period of time is constant, then it follows that

$$\int_{t_1}^{t_2} r\,\mathrm{d}t = \frac{I_2\omega_2 - I_1\omega_1}{f}. \tag{8}$$

In practice, the skater is not able to keep the rotation radii of each turn exactly the same, as indicated in figure 4(c). We measured the rotation diameter every half turn. Here we prefer to analyze the process of an upright back spin rather than a layback spin. Since the upright back spin is the easiest spin for figure skaters, skaters can execute this spin with a relatively high angular velocity, where the integral can be approximated as a summation:

$$f = \frac{2(I_2\omega_2 - I_1\omega_1)}{\sum_{i=1}^{2n} D_i T_i}. \tag{9}$$

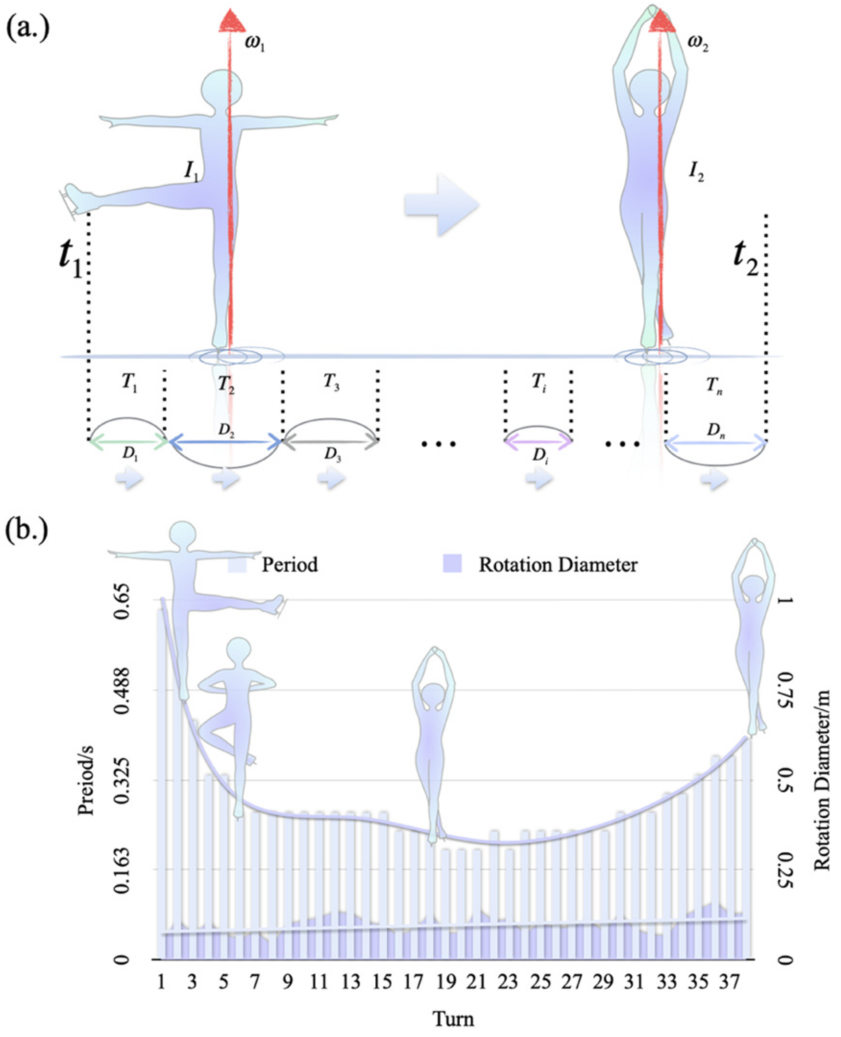

Figure 5. (a) Process of an upright back spin. (b) Change of period (light blue bar) and rotation diameter (dark blue bar) of each turn during the upright back spin.

A video of an upright back spin can be found in the supplementary information [32]. As shown in figure 5(a), the moments of inertia of the stretching position and the final contracting position, $I_1, I_{2,}$were obtained using the same procedure as the last section. The initial and terminal angular velocity, $\omega_1, \omega_{2,}$ were measured with the software. D_i represents the diameter of every half turn and T_i is its duration.

The periods and rotation diameters of each turn in an upright back spin are illustrated in figure 5(b). The skater stretched her arms and free leg at the beginning, and gradually moved her arms and free leg close to the axis. After she reached the contracting position with the minimum moment of inertia, she kept this position until the end of the spin. We divided this process into two parts: the first is the gradual transition from the initial stretching position to the final contracting position around the eighteenth turn; the second is to keep spinning steadily in this contracting position until the end. The friction during the transition cannot be regarded as a constant, because the athlete is unstable during this process, and the force applied to the ice surface is changing continuously. When the skater finishes a transition and keeps spinning in a certain position, owing to the stability of their body movements, ice resistance during this process can be seen as a constant and is considered to be of the same value in different positions. Finally, we figured out that the average ice friction is about $26N$ when the skater spins in a certain position.

5. Angular momentum

Spins in figure skating competitions are scored according to their levels [25]. Achieving a level-4 layback spin (whose score is the highest) is the goal of all the elite female figure skaters. Spins in the same level will score the same basic value; however, the degrees of difficulty of different spins cannot be exactly the same, so it will be helpful to find a way to assess the difficulty of different spins and find the easiest spin among the same-scored ones.

What is the fundamental factor that determines the difficulty of a spin? One of the authors of this paper is an amateur skater. She can execute every required position for a level-4 spin, but she cannot achieve a level-4 spin even once—she cannot accomplish all the required positions before the angular velocity is so low that she loses balance. For elite figure skaters, the biggest barrier is not the breathtaking layback positions that require good flexibility and balance, but the constant consumption of angular momentum caused by the ice resistance. They have to accomplish all the required positions for no less than the required turns before they reach the minimum angular velocity to keep balance. Consequently, given the same terminal angular velocity, the initial angular momentum the spins need reflects how difficult these spins are. Here we chose 22 same-scored level-4 layback spin, as shown in the appendix, and calculated their initial angular momentum.

As mentioned in the previous section, a layback spin is divided into two parts: transition from one position to another, and maintaining spin in a certain position. An example is shown in figure 6(a), in which the skater changes her layback position three times and keeps spinning in four different positions. When the skater keeps spinning in a certain position, one gets

$$r_i f = I_i \alpha, \tag{10}$$

where r_i is the rotation radii (distance from the toe pick to the spinning axis) of this position, f is the ice resistance during this process, I_i is the moment of inertia of the position she keeps, and α is the angular acceleration caused by the ice resistance. Among them, f and I_i have already been obtained in the previous sections, r_i was measured with the software in more than ten turns of this position, and α is determined by the formula above. Owing to the constant ice resistance, the process to keep spinning in a certain position from time t_i to $t_i{}'$ can be seen as a uniform deceleration motion. Thus, we have

$$\theta = \omega_i \left(t_i - t_i{}'\right) - \frac{1}{2}\alpha(t_i' - t_i)^2 \tag{11}$$

$$\omega_i' = \omega_i - \alpha(t_i' - t_i), \tag{12}$$

where θ is already given by the spin we chose, using the α we got before; the angular velocity when starting this position ω_i can be figured out if we know the ending angular velocity ω_i'.

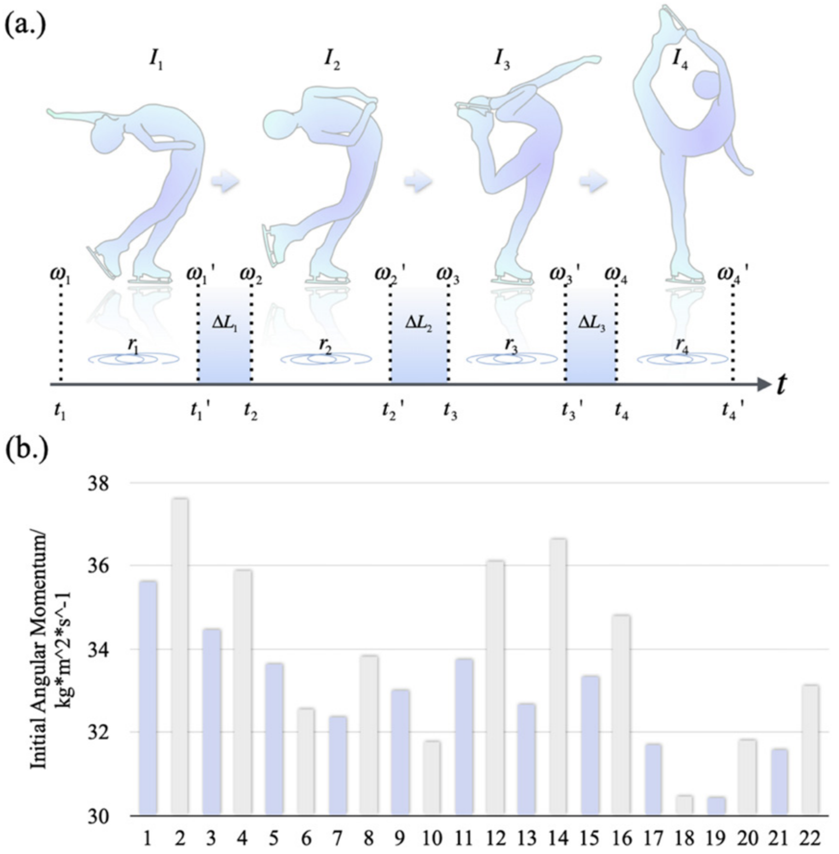

Figure 6. (a) A spin composed of four positions. (b) Initial angular momentum of 22 same-scored layback spins, which indicates the degree of difficulty of these spins.

For the transition process, consumption of angular momentum ΔL_i is described as

$$\Delta L_i = I_{i+1}\omega_{i+1} - I_i\omega_i{}'. \tag{13}$$

We analyzed each transition in at least five spins executed by the skater in different competitions. The average consumption of angular momentum ΔL_i for each transition was obtained by measuring the angular velocity when starting and after the transition. I_i and I_{i+1} were given in the previous section. Knowing the average ΔL_i in a certain transition, the angular velocity before the transition ω_{i+1} will be figured out if the angular velocity after the transition $\omega_i{}'$ is already known.

Following the procedure above, $\omega_4, \omega_3{}', \omega_3, \omega_2{}', \omega_2, \omega_1{}'$ and ω_1 can be figured out one by one after setting the terminal angular velocity $\omega_4{}'$ as 8 rad $\times$ s^{-1}, and the initial angular momentum of a layback spin is given by

$$L = I_1\omega_1. \tag{14}$$

Finally, we obtained the initial angular momentum of 22 level-4 layback spins, as illustrated in figure 6(b). Spin 19 is the easiest one among them, which starts with a difficult entry and involves Position 4 for two turns, Position 5 for two turns and Position 1 for eight turns.

		Positions of each spin and their duration			
Spin 1		Position 3 (8 turns)	Position 6 (2 turns)	Position 1 (2 turns)	Position 2 (2 turns)
Spin 2		Position 3 (2 turns)	Position 6 (8 turns)	Position 1 (2 turns)	Position 2 (2 turns)
Spin 3		Position 3 (2 turns)	Position 6 (2 turns)	Position 1 (8 turns)	Position 2 (2 turns)
Spin 4		Position 3 (2 turns)	Position 6 (2 turns)	Position 1 (2 turns)	Position 2 (8 turns)
Spin 5		Position 4 (8 turns)	Position 5 (2 turns)	Position 1 (2 turns)	Position 2 (2 turns)
Spin 6		Position 4 (2 turns)	Position 5 (8 turns)	Position 1 (2 turns)	Position 2 (2 turns)
Spin 7		Position 4 (2 turns)	Position 5 (2 turns)	Position 1 (8 turns)	Position 2 (2 turns)
Spin 8		Position 4 (2 turns)	Position 5 (2 turns)	Position 1 (2 turns)	Position 2 (8 turns)
Spin 9	Difficult entry	Position 3 (2 turns)	Position 6 (2 turns)	Position 1 (2 turns)	Position 2 (2 turns)
Spin 10	Difficult entry	Position 4 (2 turns)	Position 5 (2 turns)	Position 1 (2 turns)	Position 2 (2 turns)
Spin 11	Difficult entry	Position 3 (8 turns)	Position 6 (2 turns)	Position 1 (2 turns)	
Spin 12	Difficult entry	Position 3 (2 turns)	Position 6 (8 turns)	Position 1 (2 turns)	
Spin 13	Difficult entry	Position 3 (2 turns)	Position 6 (2 turns)	Position 1 (8 turns)	
Spin 14	Difficult entry	Position 6 (8 turns)	Position 1 (2 turns)	Position 2 (2 turns)	
Spin 15	Difficult entry	Position 6 (2 turns)	Position 1 (8 turns)	Position 2 (2 turns)	
Spin 16	Difficult entry	Position 6 (2 turns)	Position 1 (2 turns)	Position 2 (8 turns)	
Spin 17	Difficult entry	Position 4 (8 turns)	Position 5 (2 turns)	Position 1 (2 turns)	
Spin 18	Difficult entry	Position 4 (2 turns)	Position 5 (8 turns)	Position 1 (2 turns)	
Spin 19	Difficult entry	Position 4 (2 turns)	Position 5 (2 turns)	Position 1 (8 turns)	
Spin 20	Difficult entry	Position 5 (8 turns)	Position 1 (2 turns)	Position 2 (2 turns)	
Spin 21	Difficult entry	Position 5 (2 turns)	Position 1 (8 turns)	Position 2 (2 turns)	
Spin 22	Difficult entry	Position 5 (2 turns)	Position 1 (2 turns)	Position 2 (8 turns)	

6. Conclusion

In this paper, we calculated the moment of inertia of a skater in six different layback positions using spinning videos, Tracker software and the inertial parameters of the human body given by a national standard. We found an average ice resistance when the skater keeps spinning in a same position of about 26*N*. We assessed the degree of difficulty of 22 same-scored layback spins by comparing the initial angular momentum they need at least. Generally speaking, if you want to achieve a layback spin efficiently, one should choose the positions whose moment of inertia and rotation radii (distance between the toe pick and spinning axis) are small, choose the positions with less consumption during their changing process, and choose an ending position with a low moment of inertia. Record videos of the skater if possible and follow the procedure of this paper: then you can calculate the initial angular momentum of all the possible spins within the skater's capability and find the most efficient one among them. The result is based on the weight, height, layback position and spinning technique of the skater, so it varies from person to person. We are not able to encompass all the possible layback spins; instead, we give a practical method to attain it. This work can help figure skaters achieve a high-scored layback spin in an easier way. At the same time, the process of video analysis will help students enhance their understanding of moment of inertia, torque and angular momentum, accompanied by a strong sense of achievement in solving problems in real life.

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Appendix

The 22 same-scored level-4 layback spins we chose.

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